Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

A Preliminary Conceptual Model of Azufral Geothermal System, Colombia

Claudia ALFARO[1], Patricia PONCE[2], María Luisa MONSALVE[3], Iván ORTIZ[4], José Vicente FRANCO[5], Adriana ORTEGA[6], Roberto TORRES[7] and Diego GOMEZ[8]

Dg.53 No. 34-53, Bogotá, Colombia

[1]calfaro@sgc.gov.co, [2]pponce@sgc.gov.co, [3]mmonsalve@sgc.gov.co, [4]iortiz@sgc.gov.co, [5]jfranco@sgc.gov.co, [6]aortega@sgc.gov.co, [7]rtorres@sgc.gov.co, [8]dgomez@sgc.gov.co.

Keywords: Azufral geothermal system, conceptual model, geothermal exploration, Azufral Geology, magnetic study, gravimetric study, fluids geochemistry

ABSTRACT

Azufral volcano (number 351090 according to the Smithsonian Institution[1]) hosts a geothermal system which surface manifestations such as hydrothermal alteration zones, hot springs, fumaroles and hydrothermal eruption craters, have arose interest of the geothermal community since the publication of the national geothermal reconnaissance study, in 1982. The volcano is located southwest of Colombia, in Nariño Province, nearby the Republic of Ecuador, within the area of influence of five indigenous reserves. The volcano and the caldera lake (Laguna Verde) in particular, are sacred places for the native community. Progress in the prefeasibility studies carried out by the Colombian Geological Survey (SGC, for its acronym in Spanish) include the geological and structural map, magnetic and gravimetric studies, geoelectric surveys (VES), surface hydrothermal alteration and fluid geochemical analyses. Based on the integration of the existing studies and including the information of the volcanic activity surveillance program, particularly seismic, a conceptual model was formulated: A high temperature geothermal system (about 225°C) dominates the current activity of Azufral volcano. The geothermal surface manifestations such as hot springs and hydrothermal alteration zones are mainly controlled by faults and their intersections. The geothermal gradient, estimated from the magnetic anomaly (Curie depth), is higher than 120°C/km. The expected geothermal reservoir would be located about 2 to 2.5 km deep. The geothermal fluid gets a significant contribution of shallower water sources, along the upflow, which confer the local isotopic signature of the precipitation to the water discharged by the hot springs. The boiling zone, identified from the advanced argillic alteration related to current acidic sulphate fluid discharges, in fumaroles (steam vents) and hot springs, points out the upflow zone, at the volcano summit, by Laguna Verde. The outflow, favored by NW-SE structures, goes from the center of the volcanic edifice to 6-8 km east, where it is accumulated. Guachucal fault, a major SW-NE structure, seems to bound the lateral outflow extension just overflowed to the east in the junction between Guachucal and south line of El Diviso-Túquerres fault.

1. INTRODUCTION

Azufral volcano (or the Great Chaitán, its indigenous name) is located on the Western Cordillera at 1°05' N latitude and 77°43 W longitude, 12 km west from Túquerres, in Nariño Department, Southwest Colombia (Figure 1). The foothill is about 2500 m.a.s.l. and the highest elevation, 4070 m.a.s.l. The hydrothermal system seems to be extended towards Pajablanca volcano, located about 15 km southeast.

The geothermal system hosted by Azufral volcano was identified as high priority, in the national context (OLADE, ICEL, Geotermica Italiana, 1982). In 2000, the Interamerican Development Bank (IDB) approved a project for prefeasibility studies at Azufral. The non-reimbursable technical cooperation project budget was 1.5 million USD, funded by the Japanese Trust Fund for Consultancy Services (JCF). The proposal was originally submitted by the Institute of Nuclear Sciences and Alternative Energies (INEA), which was liquidated. The project ATN/JC-6902-CO, (IADB, 2000) was assigned to be carried out the Colombian Geological Survey (previously INGEOMINAS); regrettably it had to be cancelled after concluding the bidding process and awarding of the consulting company.

Since 1998, the Colombian Geological Survey (SGC, for its acronym in Spanish) initiated the information review and technical activities for producing the geological map (Calvache et al., 2003). Subsequently, from 2006 onwards other activities and studies on hydrothermal alteration, geophysics and fluid geochemistry were carried out, in the frame of the Geothermal Exploration Project. The present work is the result of the compilation and technical integration of those studies.

2. GEOLOGY

Azufral Volcano is a structure with a crater of 2*3 km in diameter and exogenous domes inside, which was built above of volcanic edifices which produced important andesitic lava flows (dated by Bechón & Monsalve (1991) in 0.58 ±0.03 M.a.) and thick ignimbrite layers. Although Azufral has not reports of historical activity, it is considered an active volcano based on the age of its deposits, which ranges between 17500 and 280 years B.P. (Bechon et Monsalve, 1991; Fontaine, 1994; Cortés y Calvache, 1997; Calvache, 1999; Torres et al, 2001), its active surface hydrothermal manifestations (hot springs, fumaroles and domes) and, recent hydrothermal eruptions (Gómez y Ponce, 2009, Cortés et al, 2009).

According to Bechon & Monsalve (1991) and Fontaine (1994), at least one old volcanic edifice related to the andesitic crater located to the North of the current caldera, would form the base of the current volcanic edifice. The basement rock of the volcano consists of metasedimentary rocks of Lower Cretaceous age (Dagua Group) and volcanic-sedimentary rocks of Upper Cretaceous age (Diabasic Group); these rocks outcrop to the Northwest of the volcano. Upper Cretaceous to Neogene intrusive rocks as granodiorites, granites and quartz diorite outcrop in the same direction. The eruptive units defined for Azufral Volcano in the last

[1] http://www.volcano.si.edu/volcano.cfm?vn=351090

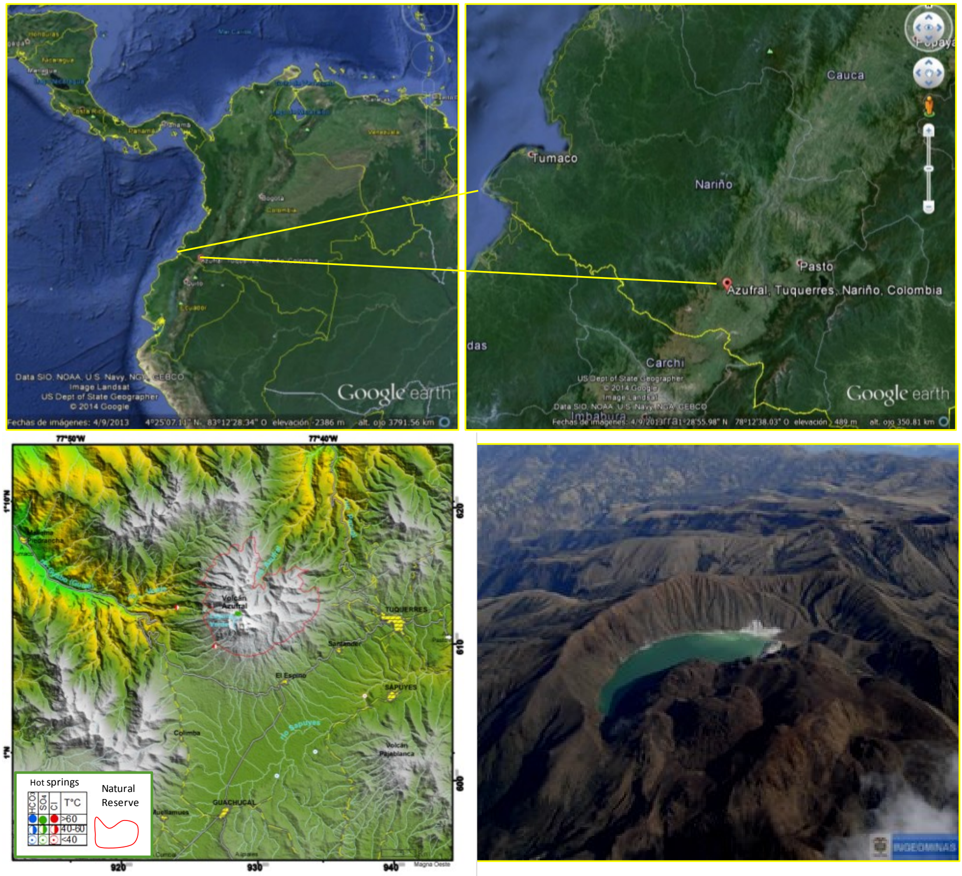

Figure 1: Location of Azufral volcano, on the high Andean plateau in Nariño Department, Southwest of Colombia (up). The occurrence of a dacite dome complex and an intracalderic lake (Laguna Verde) are the most characteristic features of this volcano (down right). The surface manifestations of the hydrothermal system related to Azufral Volcano include fumaroles in the crater by the lake and hot springs scattered within the volcanic edifice (inside the crater, West and Southwest flanks) and outside it (Southeast along a NE trend) (down left).

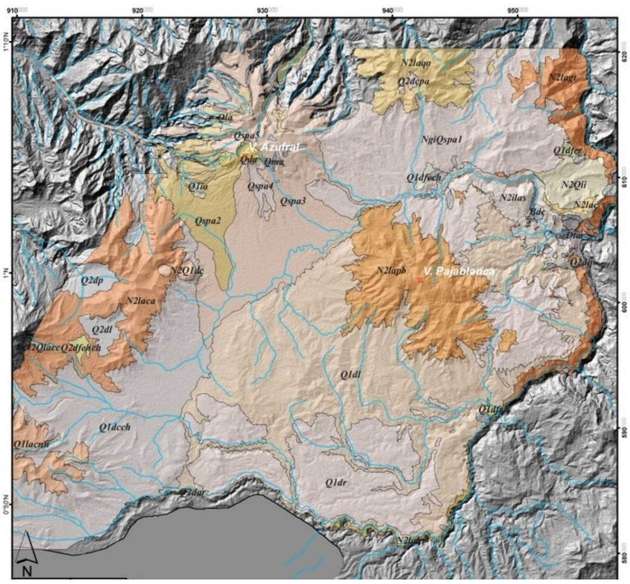

Figure 2: Geological Map of Azufral Volcano (Modified from Calvache et al, 2003a, en Carvajal y Romero 2007). Qma: Moraine deposits covered by Qspa deposits. Qspa2 and Qspa3: Pyroclastic flow and surge deposits, of Azufral Volcano. La Cortadera, El Espino and La Calera Units. Qspa4: Block and ash pyroclastic flow deposits of Azufral Volcano. El Carrizo Unit. Qspa5: Pyroclastic surge deposits of Azufral Volcano. Laguna Verde Unit. Qla: Lava flow deposits of Azufral Volcano and other pre-Azufral volcanoes. Qda: Dacite dome complex of Azufral. NgiQspa1: Ignimbrites and pyroclastic deposits of Azufral Volcano. Túquerres Unit.

20000 years were defined as Túquerres (17970±190 years B.P.), La Calera 4090 ± 70 year B.P.), La Cortadera (3.930±80 years B.P.), El Espino (between 3.750±70 y 3.500±50 years B.P.), El Carrizo (3470± 60 year B.P.) and Laguna Verde Units (280 years B.P). The distribution of these volcanic deposits is shown in Figure 2.

Some of the most relevant aspects of the geology regarding the geothermal system include the rhyodacitic composition of the mentioned deposits which show a higher magma differentiation when compared to nearby volcanoes of andesitic composition, which suggests that the magma has remained a longer in heat exchange with the crust, extending the heat anomaly; the existence of young rhyodacitic domes (~4000 years), highlights the new magma and shallow heat contribution; the pyroclastic surge deposits indicate the abundance of water, likely coming from a geothermal reservoir. The thick lava and welded ignimbrites, related to ancient Azufral's volcanic edifices and other nearby volcanoes, could host secondary permeabililty geothermal reservoir. Altered pyroclastic flows and surge deposits could become the cap rock of the reservoir.

The Western Cordillera is characterized by active and potentially active faults parallel to Romeral system, between the Central and Western Cordilleras, along the Cauca-Patía Valley. Although the faults of this system are dominantly reversed, towards the Southwest (where Azufral Volcano is located) they have high angle NNE direction and dextral movement (Taboada et al., 1998). Cauca-Patía Fault (also named Cali – Patía Fault), belongs to this system. This structure crosses the crater of Azufral Volcano , is partially covered by its pyroclastic deposits and further south crosses the volcanic edifices of Cumbal, Chiles – Cerro Negro, and extends to Ecuador (González et al., 2002). The structural scheme is shown in Figure 3. Muellamués Fault (named in this work), parallel to Cauca-Patía Fault towards the east, is a normal structure which marks the foothill of the volcanic edifice. The Guachucal Fault, with NE-SW direction, controls Sapuyes River. It is a pure strike slip to extensional strike slip fault from the South to North (Velandia et al., 2006). This fault seems to control the lateral eastern extension of the geothermal system.

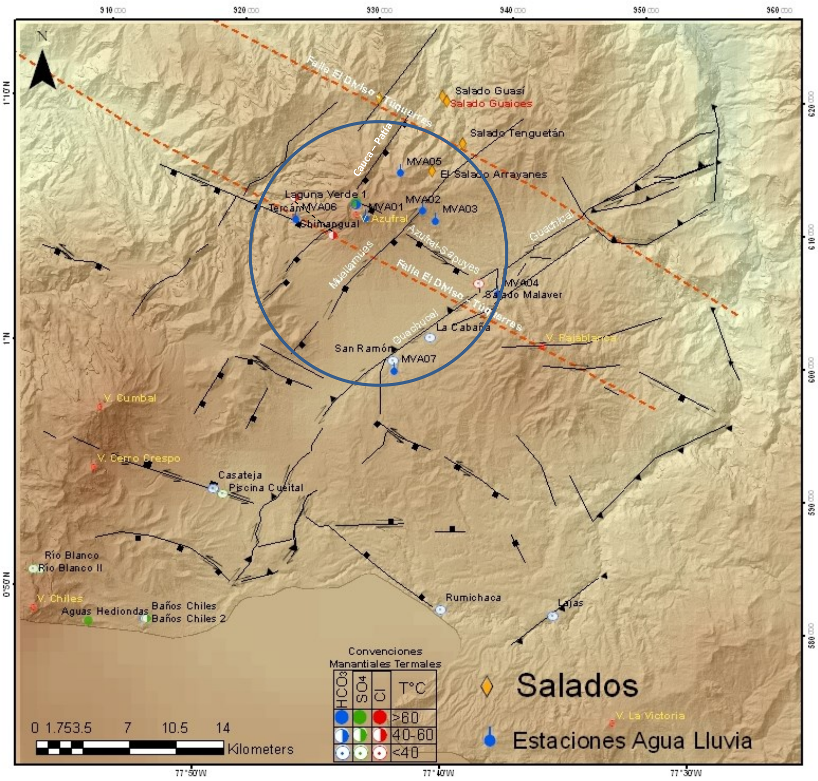

Figure 3: Structural Scheme (Modified from Velandia et al., 2006), location of hot springs and rain water stations in Azufral Volcano (this work). Blue circle: geothermal area around the volcano. The most relevant structures of Azufral volcano and its geothermal system, with SW-NE direction from west to east: Cauca-Patía, Muellamués and Guachucal Faults, with NE-SE direction: El Diviso – Túquerres, north and south lines (Cepeda, 1985), Azufral-Sapuyes and Tercán-Chimangual Faults. Chloride hot springs (red circles) emerge in Tercán, Chimangual and Sapuyes (Malaber). Acid sulfate waters (green circles) spring up in Laguna Verde. Bicarbonate springs (blue circles) occur in La Cabaña, San Ramón and Laguna Verde.

El Diviso – Túquerres Fault, consists of two parallel lineaments NW-SE direction, identified by remote sensors analysis (Cepeda, 1985), which importance is derived from its intersection with Cauca-Patía fault that would led the emergence of Azufral Volcano. Two additional local structures with NW-SE direcction Tercán – Chimangual and Azufral - Sapuyes, located west and east of the volcano, respectively, would be important structures for the circulation of the geothermal water. Tercán- Chimangual Fault identified by geophysics (Euler's solutions), connects the two hot springs with the same names; it could be related as a synthetic fault with the south line of El Diviso-Túquerres Fault.

3. GEOPHYSICAL STUDIES

3.1 Gravity and Magnetic Methods

Based on the measurements of gravity and magnetic fields in 307 stations which distribution is presented in Figure 4, regional and residual anomaly maps were built, as illustrated in the same figure. 2D models in eight profiles were obtained, as the one illustrated in Figure 5. Along those profiles and based on spectral analyses (Spector & Grant, 1970; Connard et al., 1983; Okubo et al., 1985; Blakely, 1996; Ebbing et al., 2009; Tanaka et al., 1999; all In Ponce, 2013), the Curie depth and the geothermal gradient were obtained. The Curie depth was estimated in a range of 2,3 and 14,2 km. As a result of those depths, the geothermal gradient was estimated in a wide range of 40 to 250°C/km. For the profile 1 (Figure 5), below the volcanic edifice, the Curie depth was calculated in 4 km and the geothermal gradient, estimated in 121°C/km. Additional processing such us analytical signal, favorability index based on the first vertical derivative of total Bouguer anomaly and the magnetic anomaly reduced to the pole and, Euler deconvolution, were run (Ponce, 2013). Besides the mentioned thermal inferences, important contributions to the model were obtained: linear trends that allowed to relate Tercán and Chimangual springs with a structure that would connect them, well defined throat to throat favorability index area interpreted as an accumulation of outflow geothermal fluid, to the west of Túquerres town (Alfaro et al., 2013).

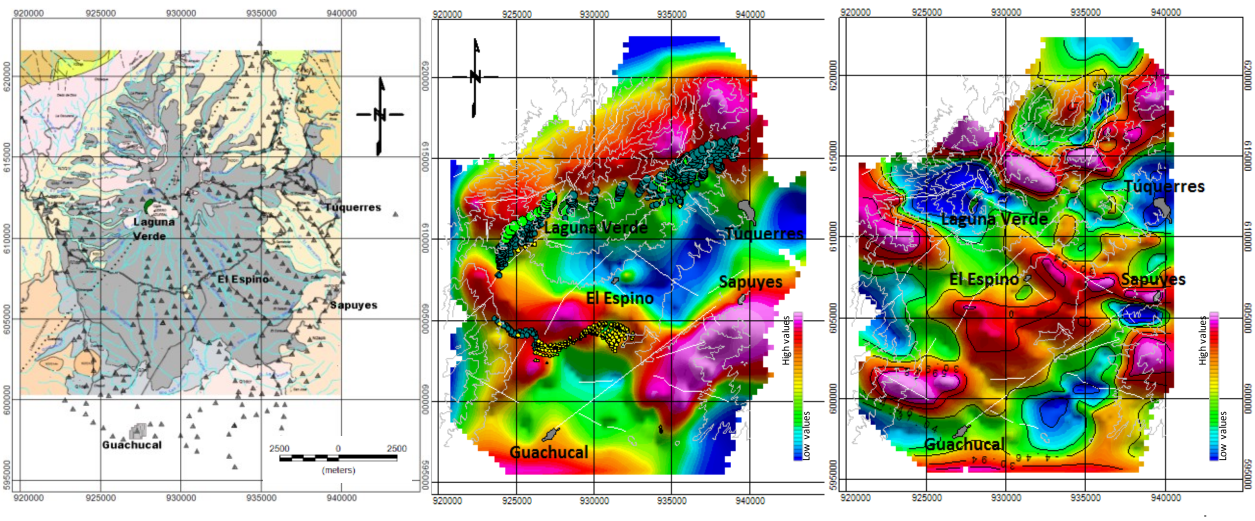

Figure 4: Gravity and magnetic study in Azufral volcano geothermal area. Left: measured stations (Gómez & Ponce, 2009) on geological map 1:100.000 (INGEOMINAS, 2003). Center: residual Bouguer anomaly map (colored circles to illustrate Euler solutions to estimate the depth of gravity sources: >2 km for green, between 1 and 2 km for blue and <1 km for yellow); Right: residual magnetic anomaly map (Ponce, 2013). Low gravity and low magnetic anomalies are found around Azufral volcano which define a favorability index area to the west of Túquerres.

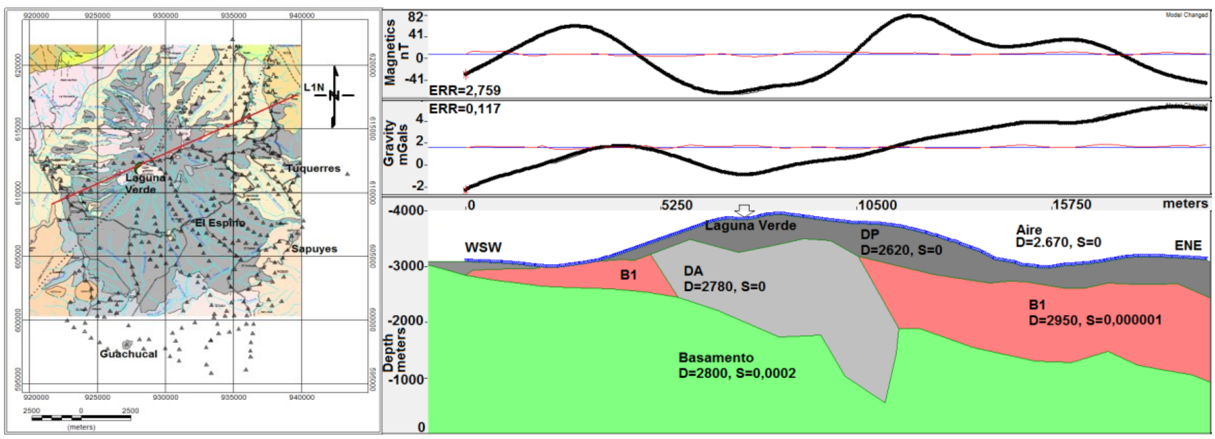

Figure 5: 2D Gravity – magnetic model. Left: Location of the main modeling profile, SW-NE direction, 20 km length. Right: 2D model. The differentiated blocks are interpreted as basement (green), andesitic lava or ignimbrites (red), Azufral's deposits confined by two faults (light gray) and unconsolidated pyroclastic deposits on surface (dark gray) (Ponce, 2013).

3.2 Geoelectrical study.

The geoelectrical study carried out Southeast of Azufral Volcano, as indicated in Figure 6, was based on 147 VES, 19 geoelectrical profiles, 2 tomographies of 1776 and 1365 m. length, a 3D resistivity graphical interpolation done with the software Voxler, from which 10 isoresistivity maps where built between 2700 to 3150 m.a.s.l. From this study, resistivity below 25 Ω.m, was related with geothermal fluids, between 25 and 128 Ω.m, with saturated and unconsolidated sandy silt material or pyroclastic flows, between 128 to 288 Ω.m, with highly fractured welded ignimbrites or lavas, between 288 to 648 Ω.m, with poorly fractured lavas and above 648 Ω.m, very consolidated igneous rocks (Franco, 2012).

The isoresistivity maps showed a relationship between the low resistivity distribution areas with the main NE faults like Guachucal and Muellamués and NW faults like Azufral – Sapuyes and some located to the South parallel to it. Guachucal fault, a major SW-

NE structure, seems to bound the lateral outflow extension just overflow to the east in the junction between Guachucal and south line of El Diviso-Túquerres fault at 2900 and 2950 m.a.s.l. (Franco, 2012)

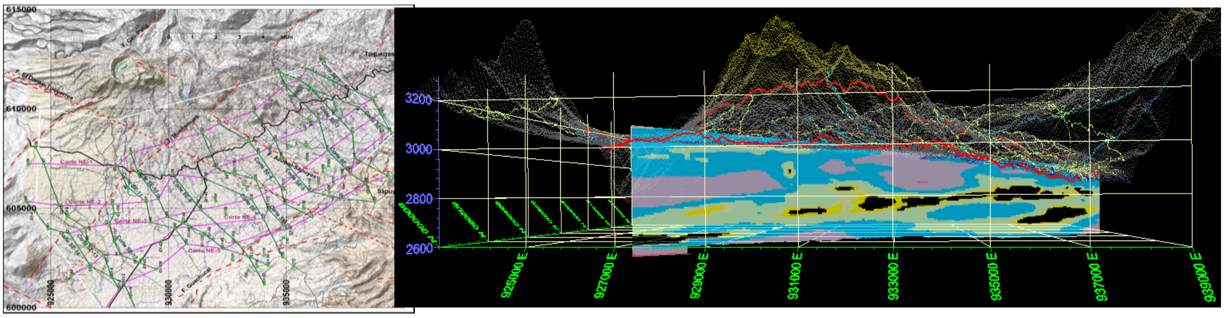

Figure 6: SW-NE Geoelectric cross section, semi-parallel to Guachucal Fault, from the Voxler 3D interpolation (Franco, 2012). Left: VES' and geoelectrical profiles locations. Right: Profile showing the conductive layer (≤16 Ω.m in yellow) related to the shallow fluid circulation. Levels related with lavas or welded ignimbrites (in red) would be covering the geothermal fluids circulation levels.

3.3 Seismology

The current volcanic activity is characterized by a mild fumarolic activity, hot springs and the low occurrence of low energy seismicity. In the frame of the Research and Surveillance of active volcanoes in Colombia, the seismological base line started to be built through sampling campaigns by using portable seismographs, since 1999. The implementation of the permanent network of seismic stations started in 2009. Since January 2011 thos network enable the location of seismic sources on a regular basis (Torres, 2013 In Alfaro et al., 2013).

The distribution of volcano-tectonic (VT) earthquakes focus, related to purely elastic processes that lead to the fracturing of solid material, is dispersed and seems to be strongly controlled by the tectonics of the region. Few of those VT earthquakes are located close to Laguna Verde and their depths do not exceed 3 km. The occurrence of distal VT earthquakes, moderate in magnitude (4.5 to 6.5 M_L) associated with distal fractures, that could be interpreted as an early stage of deformation of the magma chamber, is not evident (Torres, 2013 In Alfaro et al., 2013).

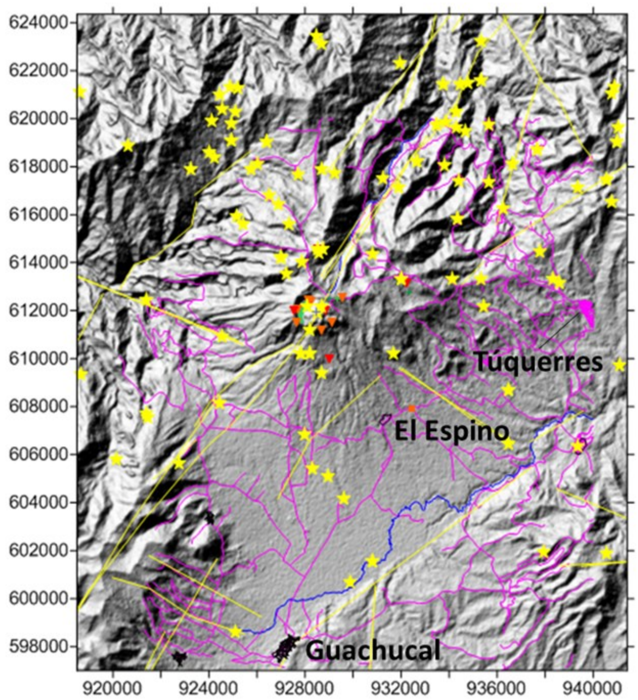

Figure 7: Earthquakes epicenters (yellow stars) calculated by minimization of arrival time residuals of earthquakes registered, between January 12, 2011 and December 9, 2013 (Torres, 2013. In Alfaro et al., 2013). Red triangles: permanent stations. Orange triangles: temporary (portable) network used during 2011 seismic sampling. The yellow lines suggest some fault. Roads in lilac lines.

In 2009, 2010 and 2011, long period earthquakes, associated to with disturbances of transitory pressures by movement of fluids, were registered by the seismic stations of Azufral volcano. In 2009 a small material emission (made of gases and molten sulfur) occurred in the northwestern side of Laguna Verde (Figure 8). In 2011, during the seismic sampling campaign, seismic signals related to the fluid dynamics (boiling, steam movement and water circulation) were registered by one of the seismic stations installed inside the crater, close to fumaroles (Torres, 2013 In Alfaro et al., 2013).

The activity of the volcano seems to be shallow and related with the hydrothermal activity without evidences of magma movements that could entail an eruption in short time (Torres, 2013 In Alfaro et al., 2013).

Figure 8. Hydrothermal activity occurred in July 2009, in the Northwestern sector of Laguna Verde, inside Azufral's crater (Taken from Torres, 2013 In Alfaro et al., 2013). Gas and molten sulfur emissions were registered. The seismicity related to this fluid movements were not registered due to its small in magnitude and long distance of the closest seismic station (~ 5km).

4 HYDROTHERMAL ALTERATION

Since the first geothermal exploration studies in Colombia (OLADE, ICEL, Geotermica Italiana, 1982), one of the most remarkable features identified in the geothermal system of Azufral, was the vertical zonation of the hydrothermal alteration and a pervasive high temperature alteration, identified in xenoliths. Based on X-ray diffraction analysis and petrography, mainly, surface and deep alteration was characterized from "in situ" (Carvajal & Romero, 2007 and Geoestudios, 2010) and lithic samples (Martinez, 2009), results compiled by Alfaro et al., 2013, described as follows.

In situ hydrothermal alteration was identified in samples located between Cali-Patía and Muellamués faults and El Diviso – Túquerres south and north lines (see Figure 9). Argillic, advanced argillic and phylic alteration are found in the headwaters of Azufral River, a fossil alteration area located north from the current crater possibly related to a change in the path of the fluids circulation of the current system, or to the trace of a boiling zone of a previous hydrothermal event. Inside the crater of the volcano, a pervasive advanced argillic zone is found, associated to active acidic fumaroles and hot springs, by Laguna Verde (see Figure 8).

Low intensity propylitic alteration is found in few samples located in the above mentioned fossil alteration area, on andesitic and dacitic rocks and in the western flank of the volcano on a diabase, along a NW normal structure probably related to the south line of El Diviso-Túquerres fault. The surface propylithic alteration, identified in the mineral association epidote-chlorite-calcite and chlorite, sericite, saussurite and palagonite, leads to suggest that lifting, collapse or erosion could affect those areas to expose on surface the high temperature reservoirs rocks.

In xenoliths found SE of the volcano just below the south line of El Diviso – Túquerres fault, in a thick sequence of pyroclastic deposits (El Espino), pervasive high temperature alteration is identified: propylitic, characterized by the presence of epidote and paragenesis as tremolite, actinolite and quartz and, potassic, identified by association of minerals like biotite, epidote, actinolite and the presence of secondary magnetite.

5 FLUID GEOCHEMISTRY

The geothermal system of Azufral volcano has four main discharge areas: Crater, Tercan (Quebrada El Baño), Chimangual (Quebrada Blanca) and Sapuyes (Malaber) and individual springs in San Ramón and La Cabaña, whose location is structurally controlled by Tercan, Chimangual, Cali-Patía, Azufral-Sapuyes and Chimangual Faults (Figure 3). Their chemical composition first known from OLADE, ICEL, Geotermica Italiana (1982) and OLADE, INECEL, ICEL& AQUATER (1987), compiled by Alfaro (2001) and updated by the SGC as summarized by Alfaro et al. (2013), show the presence of acidic sulfate waters and neutral bicarbonate mixed with sulfate, in the crater, neutral sodium chloride in Chimangual, neutral chloride with significant bicarbonate contents in Tercán and Sapuyes and neutral bicarbonate water in San Ramón and La Cabaña springs (Figure 10).

The discharge temperatures of chloride hot springs is lower than 55°C but their contents of SiO_2 (180 -190 mg/l), Li (1-2 mg/l) and B (6 -12 mg/l) reveal the probability or significant contribution of geothermal reservoir fluid. The aqueous geothermometers indicate temperatures of 180°C (quartz) and 250°C (Na/K, illustrated in Figure 10) for the reservoir. On the other hand, the gas geothermometers estimated from the composition of the hydrothermal fumaroles with a discharge temperature of 85°C, result in temperatures between 190 and 300°C (Alfaro et al., 2008).

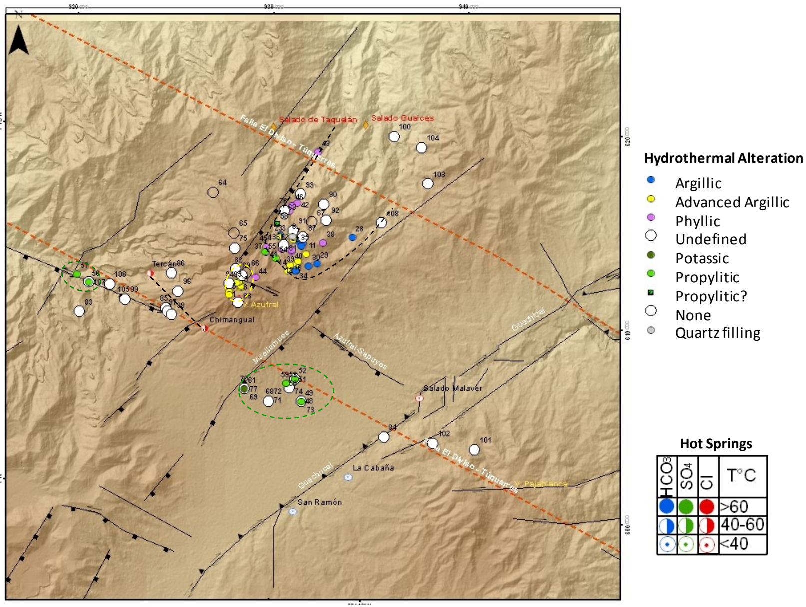

Figure 9: Surface hydrothermal alteration around Azufral Volcano. Four main alteration zones are found around Azufral Volcano: 1. Laguna Verde, advanced argillic hydrothermal alteration related to active surface manifestations (yellow circles surrounded by a dashed yellow line). 2. A fossil alteration area located towards the northeast of Laguna Verde, framed by a dashed black line, where advanced argillic, argillic, phyllic and propylitic alteration were identified. 3. Western flank of the volcano, where low intensity propylitic alteration was recognized just in two samples (green circles surrounded by dashed green line). 4. Below the southern line of El Diviso – Túquerres Fault (El Espino Locality), where pervasive Propylitic-Potassic alteration was found only in xenoliths (green circles surrounded by dashed green line). The main in situ hydrothermal alteration area seems to be structurally controlled, between Cali-Patía and Muellamués faults in SW-NE direction and south and north traces of El Diviso – Túquerres faults in NW-SE direction.

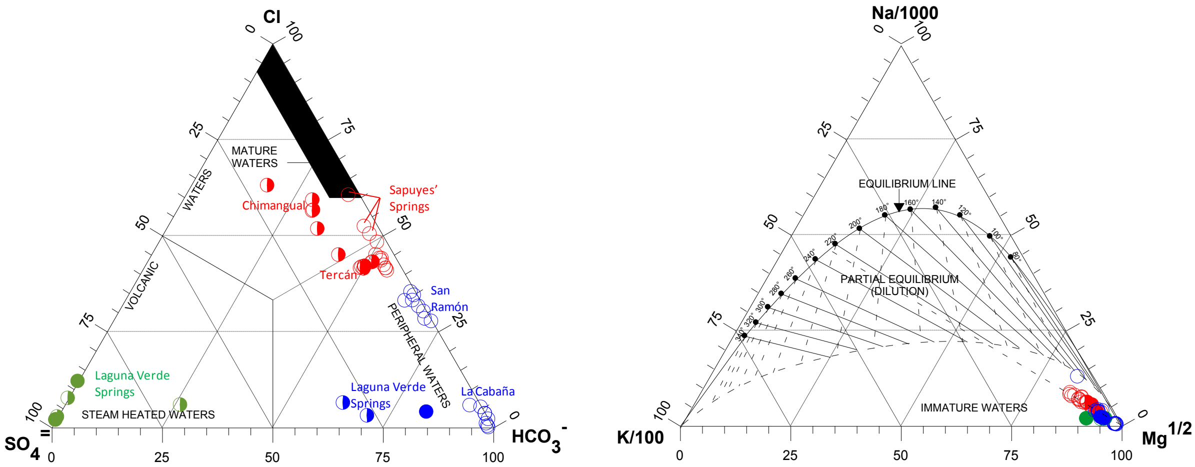

Figure 10: Relative chemical composition of hot springs from Azufral geothermal system. Left: Cl-SO_4-HCO_3 diagram (Giggenbach & Goguel, 1991). Sodium chloride springs with temperatures of 50- 55°C suggest the contribution of the reservoir fluid, which is proposed to be greater in Chimangual spring. A mixing process with a lower temperature sodium chloride source is evident in Sapuyes' springs (30°C and more than 7000 uS/cm), mainly. Acidic sulfate springs with the highest temperature (69°C) are found inside the crater, where also there are low pressure fumaroles, point out the upflow zone to the north of Laguna Verde, below the caldera. Right: Na-K-Mg diagram (Giggenbach, 1988). The influence of dilution with shallow water is evident in the high relative magnesium concentration. The Na/K geothermometer indicate a probable reservoir temperature above 200°C.

The stable isotopes composition of the water springs is similar to the local precipitation water collected from rain water samplers in the locations shown in Figure 3; that is, it does not reflect an intense water – rock interaction probably due to the important mixing process with shallow water that also reduce the hot springs discharge temperatures (Alfaro et al., 2013).

Although, the hydrothermal system is dominant in the current volcanic activity, the genetic relation of that system with the magmatic system is evident from the relation of ^{13}C in methane and carbonic gas for fumaroles gases (around -12 and -7 ‰, respectively) (Alfaro et al., 2008).

6. CONCLUSIONS

Azufral volcano hosts a high temperature geothermal system which dominates its current activity. Its heat source is related to magma and hot rocks from the activity of the last 18 thousand years, with an evident shallow heat contribution inferred from 4 generations of rhyolitic domes emplaced within the crater about 4 thousand years ago. The location of the magmatic chamber of large dimensions, as inferred from the distribution and thickness of the deposits and the existence of a previous caldera located north from the current, is below of 4000 m. A graphical representation of the conceptual model is presented in Figure 11.

As estimated from geothermometers and the well developed vertical zonation of the hydrothermal alteration, the reservoir with a temperature around 250- 280°C, would be located in a propylitic zone in the sequence of andesitic lavas or in volcano-sedimentary rocks: argillites and siltites (as proposed by OLADE, ICEL, Geotermica Italiana, 1982) between 2 to 2.5 km below the surface of the crater.

From the deep reservoir the upflow is addressed by Tercán-Chimangual, Cali-Patía and Azufral – Sapuyes Faults, mainly. The advanced argillic zone within the crater, north of Laguna Verde, related to current acidic sulfate hydrothermal manifestations produced by boiling of the geothermal fluid, confirm the upflow direction. Probably the domes paths could also act as conducts of deep fluids.

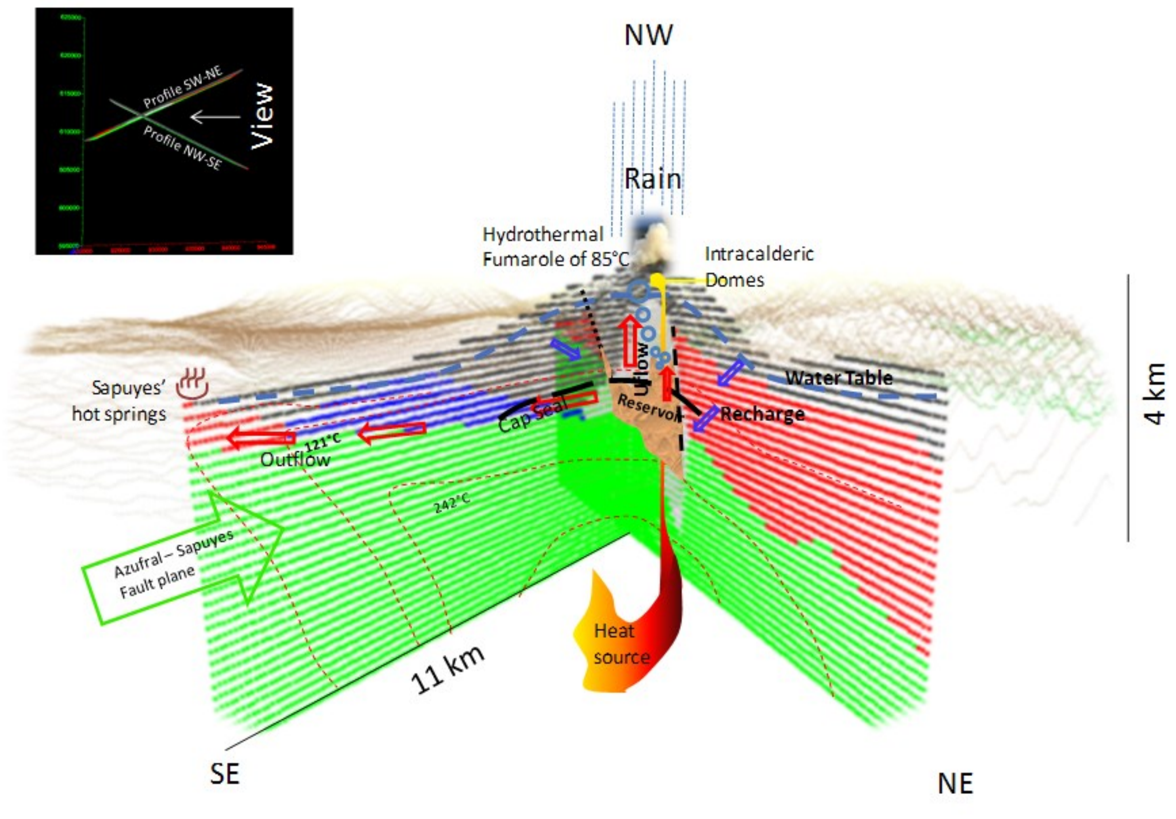

Figure 21: Preliminary conceptual model of Azufral Geothermal System. The magmatic heat source is located below 4000 m, the high temperature (>250°C) geothermal reservoir is about 2000 m deep and hosted in fractured thick andesitic lavas or ignimbrites. The shallow heat anomaly is reflected in the intra-calderic domes of about 4000 years of age. The cap seal presumably consists of hydrothermally altered surge and pyroclastic flows (Philic or argillic alteration) or low permeability levels of andesitic lava. The main upflow paths are faults (Cali – Patía and Tercán – Chimangual faults). The current boiling zone located above the main upflow is marked at the surface by active acidic hydrothermal manifestations (hot springs and fumaroles) where advanced argillic alteration is registered. The most extended outflow has a SE direction following Azufral –Sapuyes fault and the contact of the basement with volcanic products; its surface expression consists of Sapuyes' hot springs. The recharge zone seems to be local and related to deep infiltration from the highest elevation from the volcano. Horizontal lines show contrast of geophysical 2D models (magnetic and gravity) of profiles that cross Laguna Verde in direction SW-NE and NW-SE. The proposed levels include: green=basement rocks; red and blue= andesitic lava or ignimbrites; grey = pyroclastic deposits of variable consolidation and density.

The low permeability inferred from the high density towards the west of the volcano as well as the more steep topography, prevent the geothermal fluid to flow towards the western flank. The outflow extends to the east through circulation conducts related to NW structures as the south line of El Diviso –Túquerres and Azufral-Sapuyes faults. The fluid is accumulated about 7 km east of the crater in an elongated N-S area of about 21 km^2 of low density and low magnetic susceptibility (throat to throat gravity and magnetic index), identified by Ponce (2013) . This accumulation zone is structurally bounded limited by the north and south lines of El Diviso -Túquerres Fault, Muellamués fault to the west and Guachucal Fault to the east, as illustrated in Figure 12.

The cap rock might be shaped for rocks with phyllic or argillic alteration as those identified on surface between Cali-Patía – Muellamués faults or at certain depth as characterized in xenoliths by OLADE, ICEL, Geotérmica Italiana, 1982. Unaltered lavas, identified in xenoliths (Martinez, 2009) could also act as cap seal as it is suggested by the resistivity cross section along Guachucal Fault (Figure 6).

The discharge zone consists of 4 hot springs main sites: crater (where also hydrothermal fumaroles emerge), Tercán, Chimangual and Sapuyes (Malaber). It is structurally controlled by NE faults: Cali – Patía and Guachucal and crosses between NE and NW faults: Cali – Patía with El Diviso – Túquerres and Tercán- Chimangual, and Guachucal with Azufral –Sapuyes. The stable isotopes composition of the rain water and hot springs is consistent with the possibility of a local recharge by deep infiltration through distensive structures as normal faults and circular and radial structures left by the caldera formation or unconsolidated pyroclastic deposits of primary permeability.

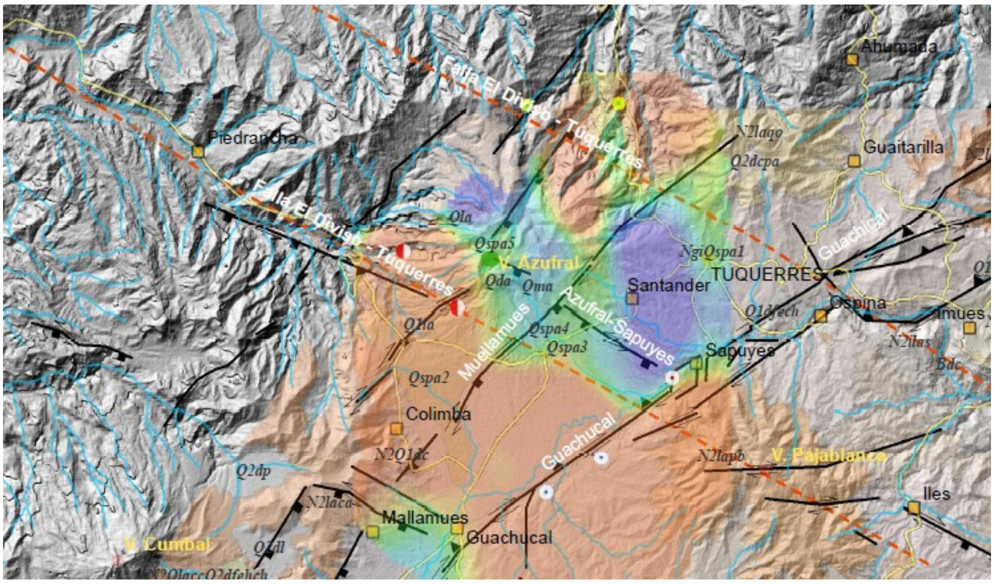

Figure 32: Throat to throat gravity – magnetic favorability index map (Ponce, 2013). The blue area limited by south and north lines of El Diviso – Túquerres, Muellamués and Guachucal faults is interpreted as an accumulation zone of the geothermal fluid from its outflow to the east (Alfaro et al., 2013).

ACKNOWLEDGMENTS

The authors thanks the contribution of the colleagues of Servicio Geológico Colombiano through discussion in development of the integration workshops, particularly to John Makario Londoño and Edwin Vallejo, as well as the group of professionals of the Volcanological and Seismological Observatory in Pasto, Nariño. Thanks also to Camilo Matiz, member of the Geothermal Exploration Group of SGC, for its contributions in the elaboration of some of the figures.

REFERENCES

Alfaro, C. 2001. Geoquímica del sistema geotérmico del volcán Azufral. INGEOMINAS. Informe técnico. Bogotá. 47 p

Alfaro, C., Garzón, G., Bobadilla, L., 2008. Geoquímica preliminar de gases del sistema geotérmico del volcán Azufral. Geología Colombiana. No. 33. Bogotá. P 91-98.

Alfaro, C., Ponce, P., Ortiz, I., Monsalve, M.L., Franco, J. V., Torres, R., Gómez, D. and Ortega, A. 2013. Modelo conceptual preliminar del sistema geotérmico del volcán Azufral. Servicio Geológico Colombiano. Informe técnico. Bogotá.

Bechon, F. et MONSALVE, M. L. 1991. Activité Récente Préhistorique du Volcán Azufral (S-W de la Colombie), C.R. Acad. Sci. Paris, 313, serie II, p.99-104.

Calvache, M.L; Cortés, G.P, Torres, M.P, Monsalve, M.L. Cepeda, H. 2003. Mapa de cartografía geológica del volcán Azufral. INGEOMINAS. Bogotá.

Cortes, G.P. y Calvache, M.L. 1997. Geología del volcán Azufral primera fase. INGEOMINAS. Informe interno. 31 p.

Cortés G.P., Calvache, M.L. y Murcia H.F. 2009. Mapa de amenaza del volcán Azufral, Colombia. INGEOMINAS Manizales, informe interno. 27 p.

Calvache, M.L. 1999. Informe volcán Azufral. Proyectos B98G04 Y C98R06. Unidad Operativa Pasto. INGEOMINAS, informe interno, 44 p. Pasto.

Carvajal, D. y Romero, D. 2007. Cartografía de las zonas de alteración hidrotermal del Volcán Azufral Nariño. INGEOMINAS, Proyecto de investigación geológica, sísmica y geotérmica el Altiplano Nariñense. Volumen 5. Bogotá. 71 p

Cepeda, H. 1985. Anotaciones acerca de la geología del volcán Galeras (Colombia). Memorias del VI Congreso Latinoamericano de geología. Tomo I.

Franco, J. V. 2012. Prospección Geoeléctrica al Sureste del Volcán Azufral, jurisdicción de los municipios de Túquerres, Sapuyes y Guachucal - Nariño. Fase – II. INGEOMINAS. Informe Técnico.

Fontaine, E. 1994. Évolution volcanologique et géochimique du volcan Azufral, Colombie, Amérique du Sud. These M.Sc., Université de Montreal. 215p.

GEOESTUDIOS. 2010. Resultados de análisis de secciones delgadas. Contrato 475 con INGEOMINAS. Bogotá

Gómez, D., & Ponce, P. (2009). Levantamiento Geofísico (Gravimétrico y Magnético) en el Área Geotérmica del Volcán Azufral, Departamento de Nariño. Instituto Colombiano de Geología y Minería. Pasto.

Gómez. D.M. y Ponce, A.P. 2009. Informe de visita técnica al volcán Azufral – Laguna verde, departamento de Nariño. INGEOMINAS, OVP, informe interno. 37 p

Giggenbach, W. F. 1988. Geothermal solute equilibria. Derivation of Na-K-Mg-Ca geoindicators: Geochimica Cosmochimica Acta, Vol. 52, p. 2749-2765

Giggenbach, W. F. 1991. Chemical techniques in geothermal exploration. In Application of geochemistry in geothermal reservoir development" Unitar. Edited by Franco D'Amore. Unitar/UNDP. Roma. p119-144.

Gómez, D., and Ponce, P., 2009. Levantamiento Geofísico (Gravimétrico y Magnético) en el Área Geotérmica del Volcán Azufral, Departamento de Nariño. INGEOMINAS. Informe Técnico. Pasto.

Gonzalez, H.; Zapata, G. and Montoya, D. M. 2002. Geología y Geomorfología de la Plancha 428 Túquerres. Departamento de Nariño. Memoria Explicativa. INGEOMINAS. Medellín

INGEOMINAS. 2003. Plancha 428 Túquerres. Bogotá.

InterAmerican Development Bank. 2000. Prefeasibility studies of the Azufral Geothermal Field. Available at http://www.iadb.org/en/projects/project-documents,7019.html?id=tc9706344&overview&projectStatus=Cancelled&isAjaxRequest&maxDocs=3

Martinez, L. 2009. Petrografía de alteración hidrotermal del volcán Azufral. INGEOMINAS. Informe técnico. Bogotá. 48 p.

Organización Latinoamericana de Energía (OLADE), Instituto Colombiano de Energía Eléctrica (ICEL), GEOTÉRMICA ITALIANA S.r.l. 1982. Estudio de Reconocimiento de los Recursos Geotérmicos de la República de Colombia.

OLADE, INECEL (Instituto Ecuatoriano de Electrificación), ICEL & AQUATER, 1987. Proyecto Geotérmico Binacional Tufiño – Chiles – Cerro Negro. Anexo B: Geoquímica. Milán. Italia. 132 p.

Ponce, P., 2013. Exploración de Recursos Geotérmicos del Volcán Azufral a partir de la interpretación de Anomalías de Campos Potenciales. Universidad Nacional de Colombia. Tesis de Maestría. Pasto.

Taboada, A., Dimaté, C., Fuenzalida, A., 1998. Sismotectónica de Colombia: deformación continental activa y subducción. Física de la Tierra. No. 10: 111-147.

Torres, M.P., Cortes, G.P., Calvache, M.L. y Monsalve, M.L., 2001. Geología y estratigrafía del Volcán Azufral. INGEOMINAS. Informe interno. 11 p.

Velandia, F.; Romero, D.; Rodríguez, B.; Hincapié, G. & Salazar, E. 2006. Esquema Estructural para Exploración Hidrogeológica en el Altiplano Nariñense. Memoria del Congreso Colombiano de Hidrogeología. Bucaramanga.